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Managed realignment to mitigate storm-induced flooding: A case study in La Faute-sur-mer, France

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ABSTRACT

Storm-induced coastal flooding is among the most destructive natural disasters while climate change together with increased populations along the coast will enhance the associated risk. This study presents the comparison of conventional coastal defense schemes against managed realignment schemes in La Faute-sur-Mer, a small village located in the central part of the Bay of Biscay that was severely impacted during Xynthia in 2010. This comparison relies on a 2DH fully coupled modeling system for the North East Atlantic Ocean, with a resolution ranging from 30 km to 5 m locally around the studied site. The comparison with available data reveals that water levels and flooding associated with Xynthia are well reproduced, with root mean squared errors below 0.2 m, and a fit measurement of 0.84, respectively. Numerical results show that the dikes maintained and raised after Xynthia won't be sufficient to protect the city against a future extreme event comparable to Xynthia in 2100 due to sea level rise. On the opposite, managed realignment and the creation of buffer zones in surrounding pastures would decrease maximum water levels up to locally more than 1.0 m, and prevent from any flooding in La Faute-sur-Mer. The optimal design and the applicability of such measures for la Faute-sur-Mer but also any other estuarine environment are finally discussed.

1. Introduction

Marine floodings are one of the most damaging natural disaster, potentially causing major loss of life and material damages (Nicholls et al., 2007). Marine floodings are caused by extreme water levels, which usually occurs when a large storm surge peaks in phase with high spring tides, although this phasing is less important in micro-tidal environments where large surges occur, such as the Gulf of Mexico (Fritz et al., 2007). Although such large surges are associated with tropical hurricanes, surges as large as 9 m were already reported in the Gulf of Mexico (Fritz et al., 2007). They are primarily driven by wind and atmospheric pressure gradients but are also influenced by waves, rainfall and river-flow. The major catastrophes that recently occurred worldwide, associated to the Hurricanes Katrina (2005) and Ike (2008) in the Gulf of Mexico, Nargis (2007) in the Gulf of Bengal, Sandy (2012) in New-York and Typhoon Haiyan (2013) in the Philippines illustrate the necessity to better understand these phenomenon, in order to mitigate their impacts. Furthermore, climate change is increasing the hazard through sea level rise and, locally, increase in storminess (Elsner et al., 2008) while, due to the increase of coastal populations, more people will be exposed to marine flooding risks (Nicholls et al., 2007).

Meanwhile, conventional coastal defense strategies, often relying on dikes, seawalls and embankments, are still widely perceived as the best option to prevent from marine flooding. However, due to the increase in flooding risk, the maintenance and raising/widening of these defenses may become unsustainable in many locations (Temmerman et al., 2013). For this reason, new resilient and cost-effective solutions have emerged over the last decade. Thus, ecosystem-based coastal defense strategies, such as 'Building with Nature' concepts (Narayan et al., 2016), were developed to address climate change while maintaining ecological values and socio-economic functions. Such approaches are being implemented in some areas such as along the coasts of The Netherlands (E. Van Slobbe et al., 2013) or also in the Scheldt estuary in Belgium (Temmerman et al., 2013), where salt marshes, dunes and other natural habitats are combined to provide resilient defenses against marine hazards. Similarly, Townend and Pethick (2002) showed that removing coastal defenses in the Humber Estuary results in the flooding of extensives marshes but decrease water levels up to 1 m. While such de-polderisation approaches only emerged recently in Northwestern Europe (Goeldner-Gianella, 2007), they are common practice in North America (Titus et al., 1991).

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The central part of the Bay of Biscay is also an area vulnerable to coastal flooding (Breilh et al., 2014), as it was dramatically illustrated during Xynthia (2010). Bertin et al. (2014) performed a high resolution hindcast of the flooding associated with Xynthia in the central part of the Bay of Biscay and showed that such massive flooding can reduce water level seaward by up to more than 1.0 m compared to a situation where flooding would be prevented, for instance by raising the dikes. This interesting behavior was also observed in two small estuaries located in the English Channel (Waeles et al., 2016) and would suggest that coastal marshes and pastures could be used as buffer zones to mitigate marine flooding (Chaumillon et al., 2017).

This study presents the managed realignment schemes and their effect on marine flooding risk reduction, based on the example of Xynthia, for both present-day and future conditions (2100). The studied area and storm are described in section 2 while the fully-coupled modeling system is presented in the following section. The next section compares new coastal defense schemes against conventional ones. The efficiency and applicability of such schemes are discussed in the last section.

2. Description of the case study area

2.1. Geomorphology

The case study is the 7.26 km^2 little town of *La Faute-sur-Mer* located along the French Atlantic Coast, in the central part of the Bay of Biscay. *La-Faute-sur-Mer* is located on the Arçay Sandspit, a 9 km long sandspit in the landward part of the Pertuis Breton embayement, which corresponds to a drown river valley segment (Chaumillon and Weber, 2006). The Arçay Sandspit splits two contrasting coastal environments, a wave dominated sandy beach to the southwest, and an estuary with mudflats to the northeast. These shallow mudflats are bordered by extensive dikes and natural barriers, which isolate large marshes and coastal plains from the sea. The analysis of LiDAR data by Breilh et al. (2013) showed that, considering a coastal band of 10 km, about 50% of this territory is located below the highest astronomical tides, which causes the study area to be one of the most vulnerable area in France to marine flooding (Breilh et al., 2013; Chaumillon et al., 2017).

2.2. Hydrodynamics

The local tidal regime is semi-diurnal and ranges from less than 2 m during neap tides to more than 6 m during springs. Tides are dominated by M2, which amplitude grows from 1.3 m along the shelf break to more than 1.8 m in the inner part of the estuaries due to shoaling and resonance of the tidal wave (Le Cann.1990 and Bertin et al., 2012). The wave regime is energetic at the entrance of the Pertuis Breton estuary (Fig. 1) where, during winter storm, the wave heights can be larger than 8 m (Bertin et al., 2015), however wave energy rapidly decreases due to refraction, diffraction and bottom friction in the inner part of the estuaries where the case study area is located. Winter wave regime in the Bay of Biscay experience a significant inter-annual variability, which was shown by Dodet et al. (2010) to be partly controlled by the North Atlantic Oscillation.

2.3. Storm surges and flooding

The main coastal hazard that affects the area of *La Faute-sur-Mer* is coastal flooding. Major floodings occurred in 1928, 1937, 1941 and 1957 (Breilh et al., 2014). Due to the lack of major event within the period 1957–2010, there was a loss of memory and habitation flooded during Xynthia were mostly constructed during this period (Garnier, 2014). More recently, in February 2010, Xynthia storm hit the French central part of the Bay of Biscay and produced a surge of about 1.6 m in phase with a high spring tide, which caused the total water level to reach the unpublished value of 4.1 m above Mean Sea Level (hereafter also MSL), at la Pallice tide gauge. Such a water level implies that all areas in green in Fig. 1 were located below the water level reached during Xynthia. This extreme water level was higher than the crest elevation of many of the existing dikes and dunes and a massive flooding occurred, mainly under overflowing regime (Bertin et al., 2014). Recent studies combining state-of-the-art statistical methods with historical data concluded that this extreme water level had a return period of the order of 250 years (Bulteau et al., 2015). After this catastrophe, the dikes were maintained and raised to a height corresponding to about 0.5 m above the water level reached during Xynthia in La Pallice, that is 4.6 m above MSL (Fig. 1).

3. Numerical modelling

3.1. General description of the modeling system

In this study, we employed the numerical modeling system SCHISM (Zhang et al., 2016) a new derivative of SELFE (Zhang et al., 2011), which realizes the full coupling in 2DH and 3D between a circulation model and the spectral wave model WWM-II (Roland et al., 2012). SCHISM solves the shallow water equations over unstructured grid and was designed to address a large range of spatiotemporal scales (Zhang and Baptista, 2008a,b). In this study, SCHISM is used in 2DH barotropic mode and the resolved equations correspond to the Saint-Venant equations. A detailed description of the model configuration to simulate waves and water levels is given in Bertin et al. (2015).

3.2. Model implementation

The unstructured grid used in this study is similar to the one described in Bertin et al. (2014), the mesh was only refined around La Faute-sur-Mer and new topographic data of the dikes were integrated. In order to keep short computational time, areas flooded during Xynthia but located far away from la Faute sur Mer were not represented in the grid. The resulting unstructured grid includes 405,346 nodes (799,915 elements) and its resolution ranges from 30,000 m in the deep Ocean to less than 5 m over the dikes and dunes of the study area (Fig. 2). The topography of intertidal and supra tidal zones originate from a LiDAR survey, that took place after Xynthia in the scope of the national program Litto3D. The resulting digital terrain model has a resolution of 1×1 m^2 and a vertical accuracy shown to be of the order of 0.15 m by Breilh et al. (2013).

The modeling system was forced over the whole domain by hourly fields of sea-level atmospheric pressure and 10 m wind speed (with $0.10^\circ/1$ h resolutions) originating from the global forecast model ARPEGE of Météo France (Courtier et al., 1991). The hydrodynamic time step was set to 3 min. The circulation model was forced by the astronomic tidal potential over the whole domain for the tidal constituents MM, MF, O1, K1, P1, Q1, M2, S2, N2 and K2. Along its open boundaries, the circulation model was forced by the 18 main tidal constituents in the region (Z0, O1, K1, P1, Q1, M2, S2, N2, K2, 2N2, L2, MU2, NU2, M3, M4, MS4, MN4 and M6), obtained by linear interpolation from the regional tidal model of Pairaud et al. (2008). The wave model was forced with wind fields over the whole domains and with times series of directional energy spectra along its open boundary, originating from the regional wave model of Bertin et al. (2013).

3.3. Model validation

Wave predictions were already validated in details by Bertin et al. (2014) and will not be described further since waves have a limited impact in the flooding of la Faute-sur-Mer. Water levels were collected at the two nearest tide gauges at La Pallice and Les Sables d'Olonne (Fig. 1), available during Xynthia through the REFMAR portal (data.shom.fr/). These data consist of 10-min continuous time series, except the station of Les Sables d'Olonne, which displayed a gap due to a power failure during Xynthia. Model data comparison reveals that water levels are very well reproduced by the model at the two stations, with Root Mean Squared

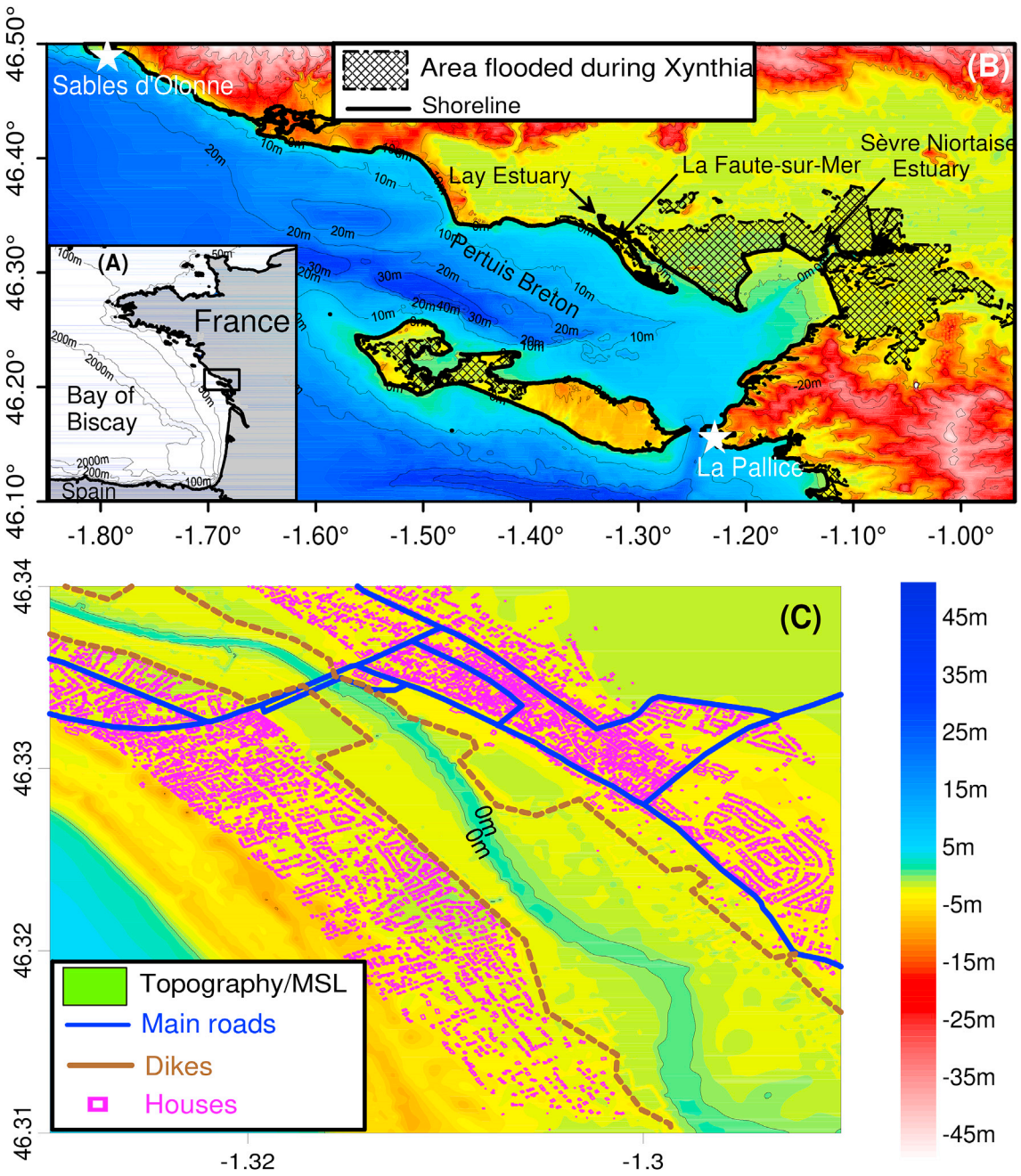

Fig. 1. Bathymetric/topographic map of the study area and extension of the flooding during Xynthia. Altitudes are given with respect to Mean Sea-Level and tide gauges operating during Xynthia are indicated by white stars. Main roads and dikes are respectively indicated by a straight bold blue and brown line and houses are highlighted in pink. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Difference (hereafter RMSD) of 0.19 and 0.18 m, for La Pallice and Les Sables d'Olonne, respectively (See Fig. 3). Once normalized by the mean local tidal range (NRMSD), the errors are of the order of 2–3% for the two stations. These water level predictions are slightly improved compared to Bertin et al. (2014), which is attributed to recent improvements in the modeling system (Zhang et al., 2016) as well as improvements in the grid and in the bathymetry.

Model predictions in terms of flooding were compared against observations compiled after Xynthia. Firstly, the extent of the flooding, was obtained from combining data from several sources of satellite images (SPOT4, ENVISAT ASAR and RADARSAT) and field observations of high water debris lines (Breilh et al., 2013). In order to quantify the agreement between the model and the observations, we employed the Fit measurements (eq. (1)) introduced by Aronica et al. (2002):

$$F = \frac{A}{A + \mathrm{B} + C} \tag{1}$$

With A corresponding to the area correctly predicted as flooded in the model, B the area predicted as flooded by the model while being dry in the observation and vice versa for C. Equation (1) implies that F can range between 0 (no overlap between model and observations) and 1 (perfect match). For La-Faute-sur-mer the comparison with the observations reveals that, the model was able to reproduce the extent of the flooding very accurately (Fig. 4), with a fit measurement of about 0.84.

We also compared modeled maximum water levels with field observations surveyed after Xynthia in the inhabited areas of La-Faute-sur-mer. Scatter plot of measured versus predicted maximum water levels are presented in Fig. 5, which showed RMSD of 0.45 m without

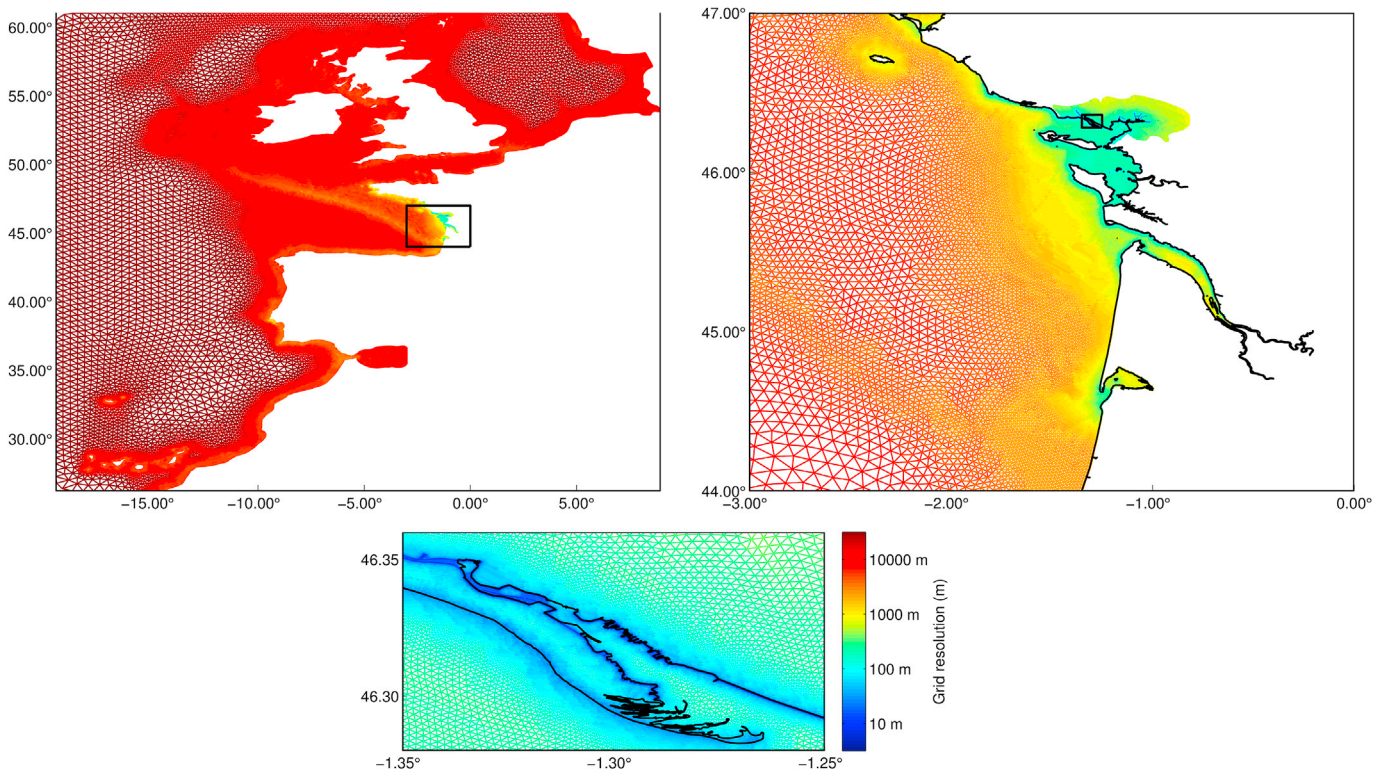

Fig. 2. Unstructured grid used in this study, implemented over the Northeast Atlantic Ocean. The colors indicate the grid resolution, which ranges from 30,000 to less than 5 m. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

significant bias. This figure also shows that 69% of the points have an error lower than 0.5 m.

4. Comparison of coastal defense schemes

4.1. Description of coastal defense schemes and scenarios

After Xynthia, the dikes around La Faute-sur-Mer were raised by 0.5 m (4.6 m with respect to MSL) compared to the maximum water level measured during this event (i.e. 4.1 m with respect to MSL) in La Pallice (Fig. 1).

In order to compare the relevance of this coastal defense scheme (hereafter CDS), alternative CDS were considered, where the crest of the dikes are locally lowered in order to allow pastures and crops to be intermittently flooded during extreme events. Indeed, accordingly to Bertin et al. (2014), the flooding of large areas would decrease water levels seaward and therefore be used as buffer zones and mitigate marine flooding in sensitive areas such as inhabited areas of la Faute-sur-Mer (Fig. 6). In order to find the more efficient dike configuration, several dike levels are considered: 3.00 m, 3.20 m and 3.40 m above MSL, which according to Bulteau et al. (2015) would correspond to water levels in La Pallice (Fig. 1) with return periods of the order of 3, 5 and 15 yr, respectively. To complement these coastal defense schemes, a second rank of dikes protecting the stakes is also implemented (Fig. 6). However, such CDS would pose a conflict of use in these pastures, which correspond to fertile areas for cereals (http://www.pays-de-la-loire.chambres-agriculture.fr/fileadmin/user_upload/National/FAL_commun/publications/Pays_de_la_Loire/2016_agriculture_en_Vendee_chiffres_2014.pdf, last accessed on July 19, 2017). As a consequence, these agriculture crops would be bought back to their owners.

The efficiency of the various CDS were compared each other considering a hazard corresponding to Xynthia for a present day configuration and for a future situation (2100). Considering that there is a large uncertainty about predicted changes in storminess at mid latitude for the end of the century (IPCC, 2014), only sea-level rise is considered in this scenario. We considered a 0.74 m sea level rise (hereafter SLR)

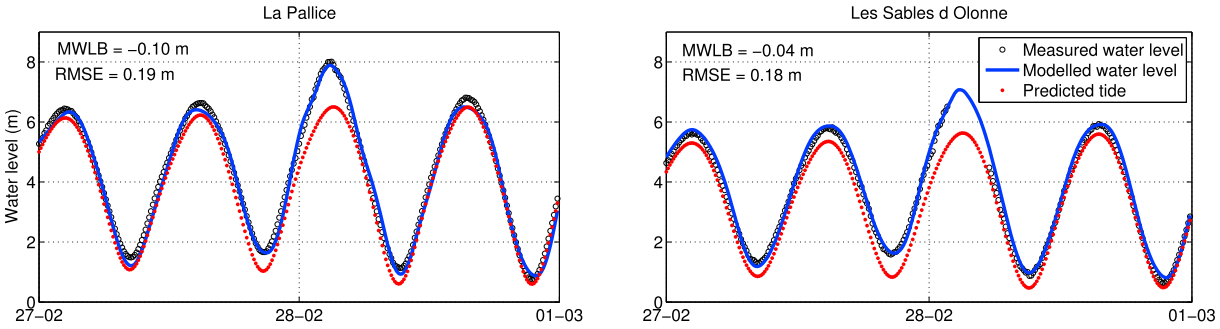

Fig. 3. Modeled (blue) against observed water levels (black circles) and predicted tide (red) at La Pallice (left) and Les Sables d'Olonne (right) during Xynthia. MWLB corresponds to Maximum Water Level Bias between modeled and observed water level reached during Xynthia storm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

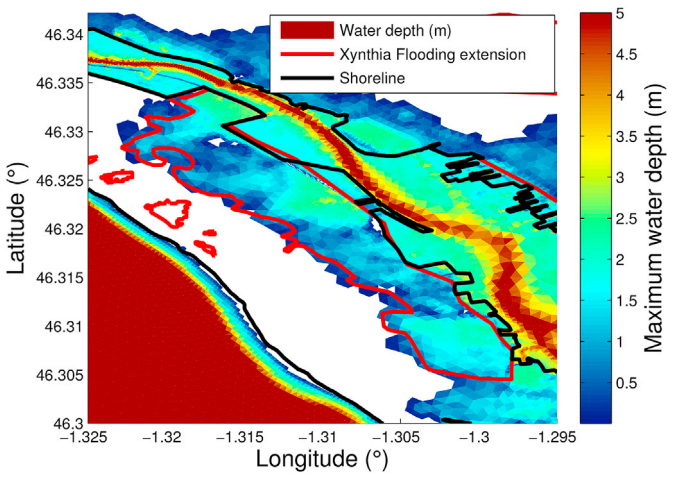

Fig. 4. Maximum water depth simulated during Xynthia (colorscale), observed extent of the flooding (red) and shoreline (black). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

according to Hinkel et al. (2014) that combined several sea-level projections for 2100 with respect to 1985–2005, under the RCP 8.5 scenario. Then, we did not consider vertical land motions because state of the art estimation available for the two nearest tide gauges (La Pallice and Les Sables d'Olonne, Fig. 1) revealed a very small and non-significant subsidence (−0.11 ± 0.16 mm/yr and −0.05 ± 0.24 mm/yr, respectively, http://www.sonel.org/, Woppelmann et al., 2009)).

However, mean sea-level already rose since the middle of the reference period 1985–2005. In the study area, the combination of available observations yields a mean SLR of 2.1 mm/yr for the period 1941–2011 (Gouriou et al., 2013). From 1995 (middle of the interval 1985–2005) to 2010, this corresponds to a SLR of the order of 0.03 m. As a consequence, for our 2100 scenario, we considered a SLR of 0.71 m with respect to 2010.

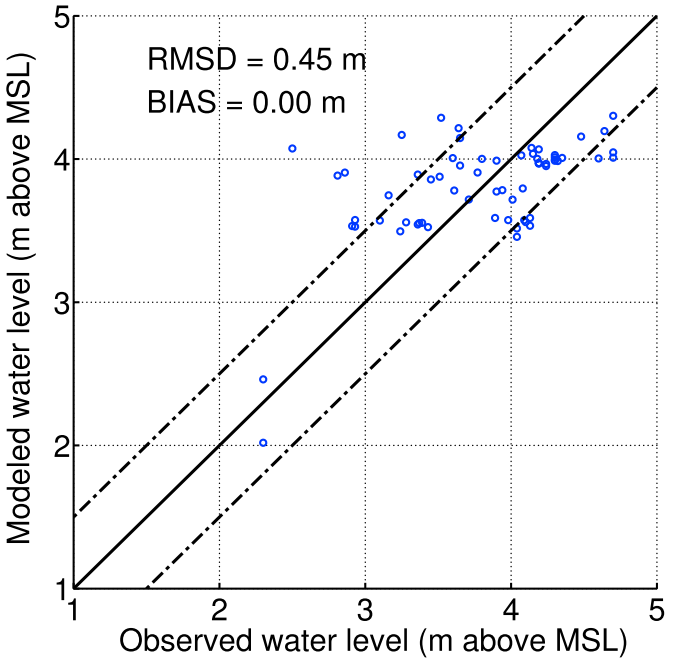

Fig. 5. Comparisons between observed high water marks and maximum water levels modelled during Xynthia in La Faute-sur-Mer. The solid black line corresponds to a perfect fit and dotted lines shows the points with a difference within 0.5 m.

4.2. Impact of CDS on marine flooding

The first measure corresponds to the dike configuration as observed in early 2016. For an event equivalent to Xynthia, no flooding would occur anymore in the inhabited area of La Faute-sur-mer (Fig. 7-B) which suggests that the measures already implemented after Xynthia are adequate to protect from such an event. For a 2100 scenario with a mean sea level (MSL) raised by 0.71 m due to climate change, the main part of the inhabited area is flooded, although maximum extension of the flooding is smaller than for Xynthia as it occurred in 2010 (Fig. 7-A). Conversely, maximum water depths in urbanized areas are up to 3 m, which is higher than the maximum water depths observed during Xynthia (around 2.5 m).

For the same scenario, the implementation of buffer zones reduces water levels by up to 0.5 m in front of La Faute-sur-Mer, so that inhabited areas in La Faute-sur-Mer would not be flooded anymore (Fig. 7-D). This coastal defense scheme directly results in a decrease of maximum water levels in the Lay River estuary, up to 0.2 m to the south of La-Faute-sur-Mer and to 0.5 m to the North of the city. This reduction of maximum water levels is able to prevent from any flooding in the inhabited area of La-Faute-sur-Mer while buffer zones are totally flooded with water depth locally reaching 4 m.

5. Discussion and conclusion

5.1. Limitations of the considered scenarios

First of all, it is important to note that the massive flooding that occurred during Xynthia in La Faute-sur-Mer was caused mainly by overflowing over the dikes and that the role of breaches was not determinant in this area (Bertin et al., 2014). As a consequence, the development of breaches in the dikes was not considered in the present analysis, while breaches did occur locally, which worsened the situation during Xynthia. While the very good prediction of flooding extension during Xynthia (Fig. 4) together with a fair reproduction of maximum observed water levels suggest that this hypothesis is valid for Xynthia-like scenarios with a present-day MSL, it may be more questionable for our 2100 scenario, where MSL is raised by 0.71 m. Secondly, in the town of La-Faute-sur-Mer, houses are represented implicitly through an increase in bottom friction. According to Le Roy et al. (2015), this simplification could result in an under-prediction of current velocities by a factor of two compared to a simulation where all houses are represented explicitly in the computational grid. However, representing all houses explicitly (>2000) would be too computationally expensive and further research would be needed about subgrid modelling of houses. Finally, our 2100 scenario assumes that MSL will rise by 0.71 m while the bathymetry/topography will be unchanged. This hypothesis is obviously weak, but performing long term morphological predictions for such a complex coastal system is outside the scope of this study. However, the main purpose of this study is not to reproduce the reality in 2100 but to take advantage of the case of Xynthia in La Faute-sur-Mer to demonstrate the relevance of CDS alternative to conventional CDS relying on dikes only.

5.2. Relevance of new CDS compared to conventional ones

Our numerical results show that the present-day configuration, where dikes were maintained and raised after Xynthia, allows for a considerable reduction flooding and subsequent damages over the entire inhabited area of La Faute-sur-Mer under the present day MSL. Conversely, model results suggest that the present-day coastal defense schemewould not be sufficient if an event similar to Xynthia would occur in 2100. Higher water depths would even be reached in the Southern part of the City. According to our modelling results, the implementation of buffer zones would decrease maximum water levels by almost 1.0 m in the inner part of the Lay Estuary, compared to a situation where flooding would be

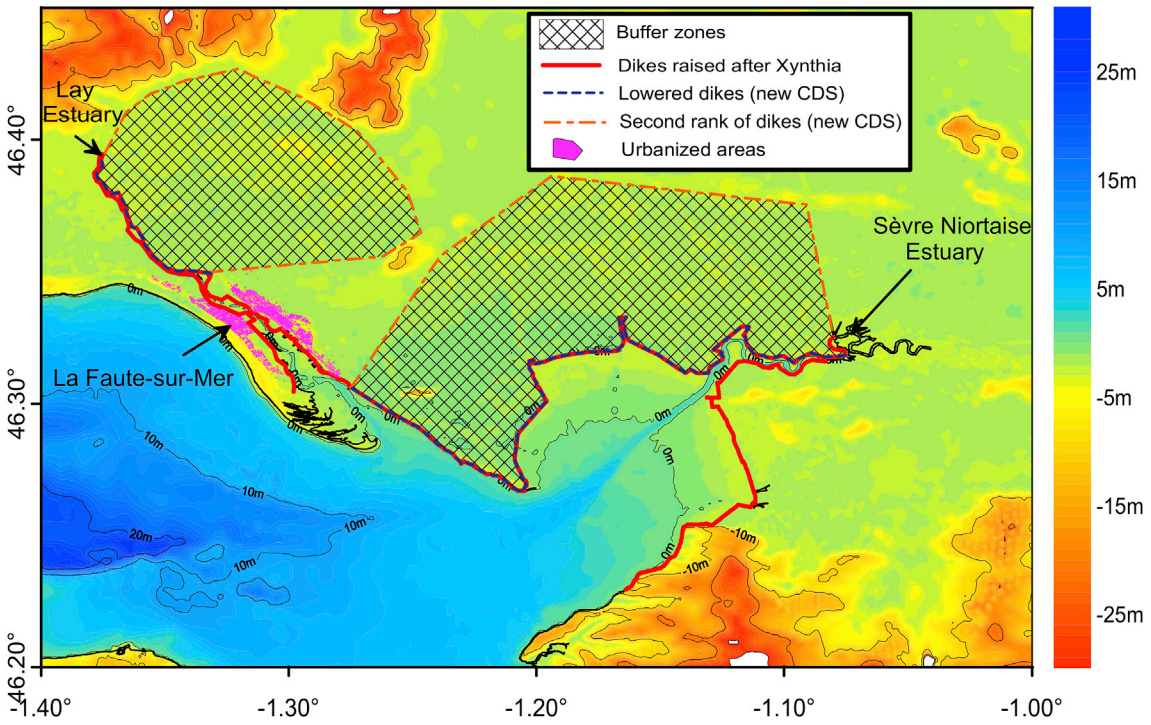

Fig. 6. Map showing the configuration of the CDS for La-Faute-sur-mer: dikes raised after Xynthia (red), dikes lowered to create buffer zones (dotted blue) and second rank of dikes to protect stakes (dotted orange). Urbanized areas are indicated in pink. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

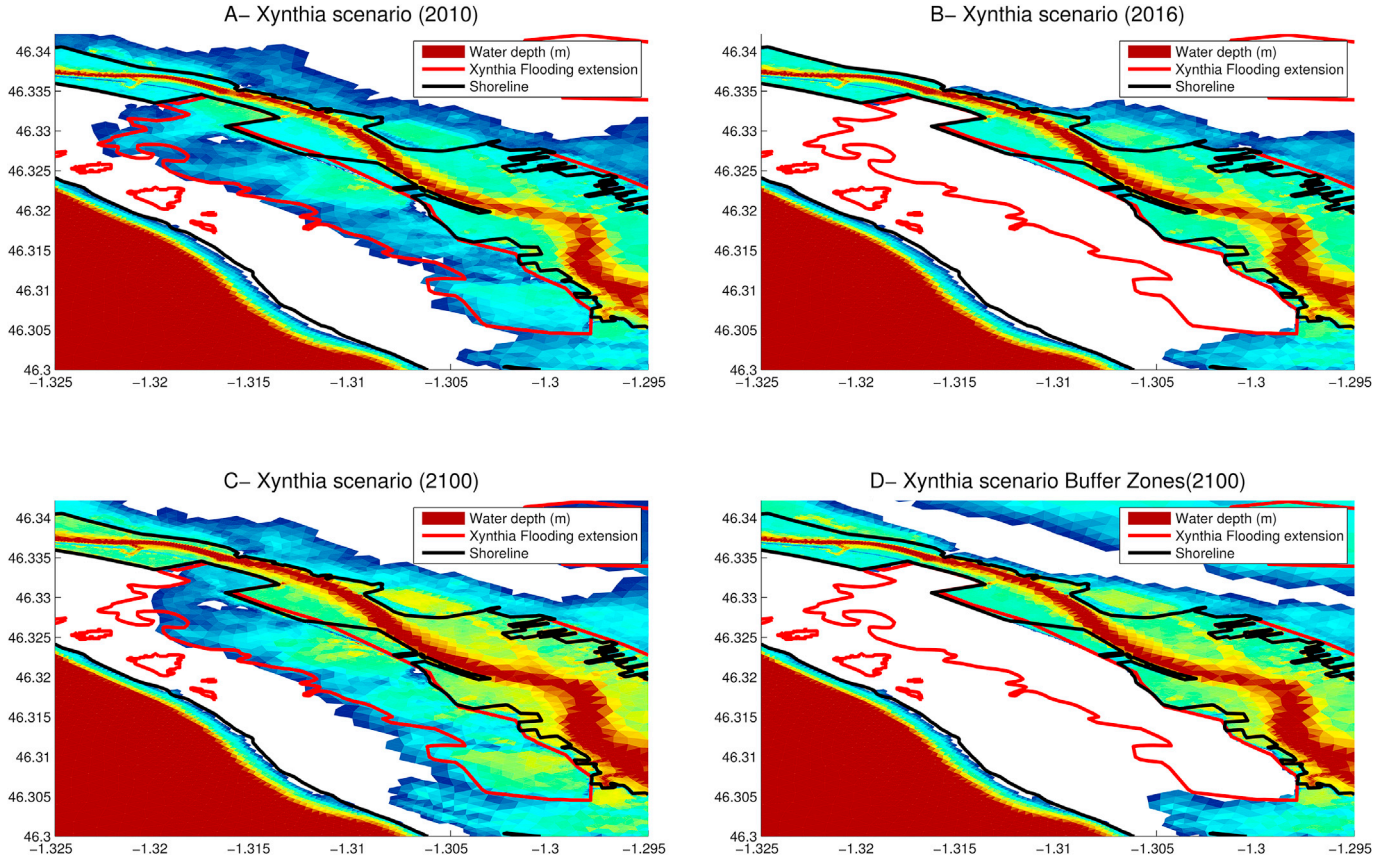

Fig. 7. Modelled maximum water depth in La Faute-sur-Mer (range of colors), maximum extension of the flooding as observed during Xynthia (red), shoreline (black), for a Xynthia scenario with the previous configuration (2010) of the dikes (A), a Xynthia scenario with the current configuration of the dikes (2016) (B), a Xynthia scenario with the current configuration of the dikes for a 2100 MSL (C), a Xynthia scenario with the current configuration of the dikes and buffer zones, for a 2100 MSL (D). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

prevented. Such a decrease in maximum water levels would more than balance the MSL rise that we considered in 2100 and thereby protect La-Faute-sur-Mer against marine flooding.

While our modeling results suggest that such solutions have a great potential, their implementation will face severe conflict of use with local farmers and agriculture lobbies. In order to find the optimal efficient CDS, several configurations dikes were tested in order to compare their impact on Water Level Reduction (hereafter WLR) in the Lay and the Sèvre Niortaise Estuaries. In order to perform consistent comparisons, we computed the difference between maximum water levels for each scenario and maximum water levels for a situation where the dikes would have been raised so that no flooding can occur anymore. WLR can be seen on Fig. 8-A, for the entire area as well as along transects along the two estuaries. The Sèvre Niortaise Estuary appears to be the most sensitive to the implementation of buffer zones with a decrease of maximum water levels, up to 1.2 m upstream. The Lay Estuary shows approximately the same offshore WLR but lower values upstream, reaching about 0.9 m at maximum.

These WLR appears little sensitive to the various dikes level considered (3.00 m, 3.20 m and 3.40 m above MSL) as it is shown on Fig. 8-B and 8-C. The behavior of the WLR along the two transects is sensitively the same, with a strengthening of the increase as the width of the estuary decreases. Indeed, WLR increases when the ratio between the length of the dikes that are flooded and the width of the estuary increases. WLR will therefore be very limited along open coasts and maximum within narrow estuaries bordered by overflowed dikes. For a given dike level, the WLR experiences only a few centimetres differences upstream for both estuaries. It means that all the buffer zones configurations mitigate marine flooding, lowering indirectly the water level with the same order of magnitude.

5.3. Applicability of new CDS

Although very promising in terms of flooding risk reductions, the applicability of buffer zones is a sensitive subject yielding conflicts of use, particularly in this area where crops are very productive and therefore represent important economic stakes. According to the data provided by La Faute-sur-Mer Townhall (comm. pers.), the raising of dikes after Xynthia event for whole study area (Lay and Sèvre Niortaise River Estuaries, Fig. 1) cost 51 M€ (Table 1). On the other hand, the implementation of the alternative CDS would cost between 46 and 130 M€ (mean value of 94 M€), depending mainly on the price of these crops, which fluctuates with time but also as a function of the surface area of each agricultural parcel (Table 1). Therefore, the new CDS would cost between the same and 2.5 times more compared to conventional one (Table 1).

However, the new scheme would present additional advantages compared to the conventional one. First, restoring agricultural crops into humid zones would create new habitats, which would increase the environmental value of this area, part of the Marais Poitevin Regional Natural Park. Second, unlike the conventional CDS, the new CDS would preserve the seaview. As the study area experiences a very large touristic frequentation (Riou, 2016), the preservation of the seaview is a key parameter in the attractiveness of the area.

However, Northern Europe Countries, such as UK, implemented managed realignment strategies to restore humid zones since the 90's and identified several drawbacks. Thus, Pontee (2015) investigated numerically the possible managed realignment of the Parret Estuary through the development of breaches in dikes and showed that it would alter tidal propagation and in turn increase maximum water levels in the inner part of the estuary. These results contrast with our findings, where our CDS

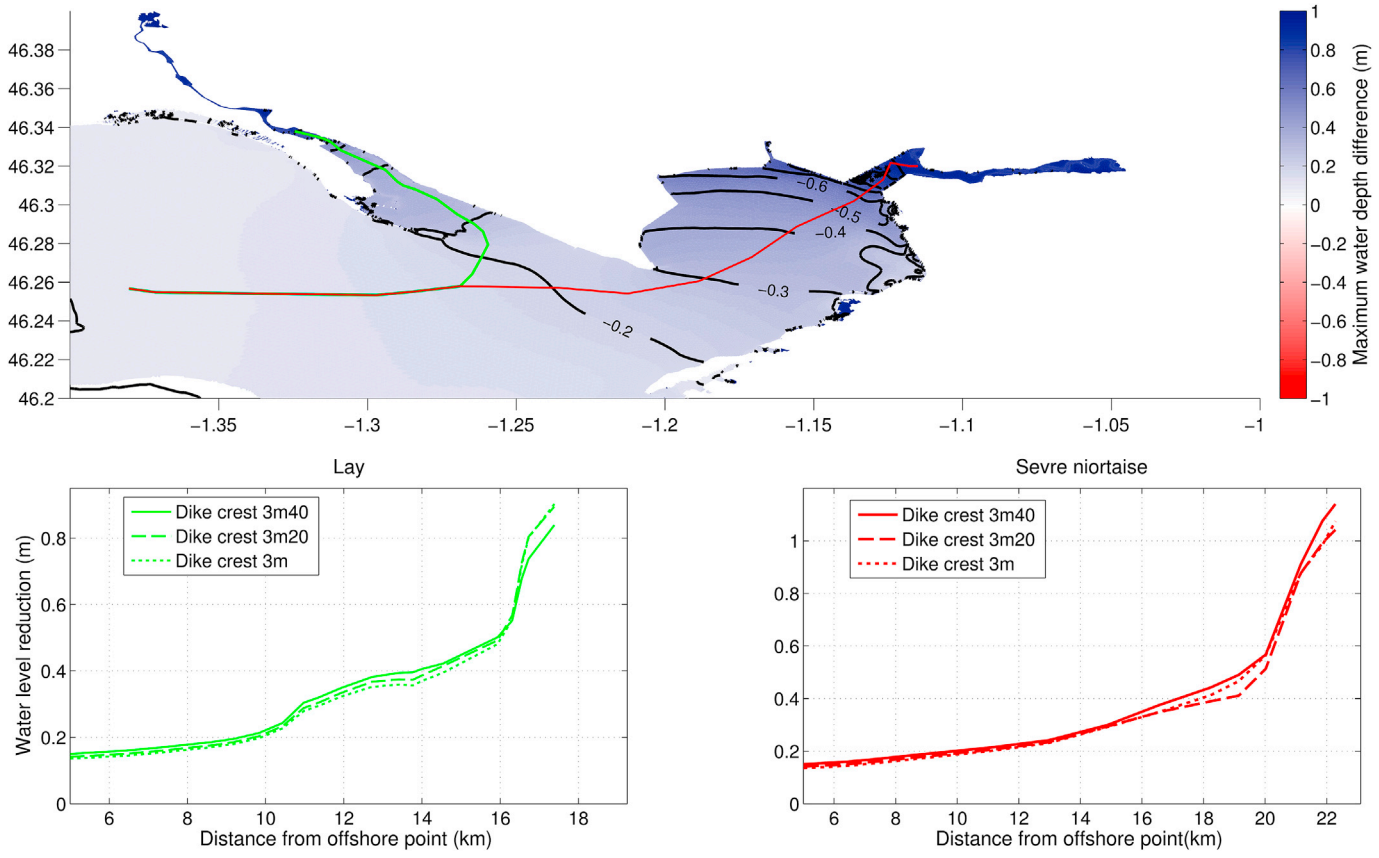

Fig. 8. Difference in maximum water level between our baseline simulation where flooding is enabled and a simulation where the flooding was disabled by raising the dikes and barriers 1 m above Xynthia maximum level (up). Red and green lines represent this difference in maximum water levels along transects for the Lay estuary (left) and the Sèvre Niortaise estuary (right) for several height of dike crests. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Geographical data and estimation of cost for each CDS. 1 corresponds to conventional CDS and 2 corresponds to new CDS.

CDS	Measure of CDS	Unity cost [k€]	Length or surface	Total Cost
1	Raising dikes protecting La-Faute-sur-mer	2100/m seawall dike height/km	12 km (50% seawall 50% earth)	36 M€
	Raising dikes protecting Aiguillon Bay	440/m earth dike height/km	40 km (26% seawall 74% earth)	15 M€
	Total		**52 km**	**51 M€**
2	Lowering existing dikes	80/m dike height /km	24 km	2 M€
	Build second rank of dikes	500/3 m dike height/km	40 km	20 M€
	Buy back cereal crops	3.59/ha (1.20–5.4/ha)	20 000 ha	72 M€ (24–108 M€)
	Total			**94 M€ (46–130 M€)**

(sources: http://www.leparticulier.fr/jcms/p1_1557259/pays-de-la-loire-prix-des-terres-agricoles-bareme-indicatif-2016 and La-Faute-sur-Mer Townhall).

would result in a maximum water level reduction up to more than 1 m, which suggests that managed realignment does not result necessarily in an improved protection against marine flooding and should be subjected to extensive numerical experiments. Other authors pointed out that managed realignment could result in reduced biodiversity for small sites and that the development of new humid zones can be at the expense of established habitats. While these problems do not apply for our study site, where the identified buffer zones are large and correspond to crops with little biodiversity, they should be considered for other sites (Esteves, 2013; Esteves and Thomas, 2014).

While the catastrophe associated with Xynthia is still a traumatism for the populations in La Faute-sur-Mer in particular and, in the central part of the Bay of Biscay in general, one should keep in mind that other regions of the world are prone to massive storm-induced flooding, impacting much more densely populated areas. Thus, the Bay of Bengal faced major catastrophes in the modern history, such as during cyclones Bola in 1970, where between 300,000 and 500,000 people passed away (Flather, 2001) or cyclone Nargis, in 2008, where 140,000 people passed away in Myanmar (Wolf, 2008). Our numerical results revealed that WLR was largest inside estuaries bordered by dikes and levees that experience large overflowing. Such CDS would have to be considered as potential solutions to mitigate flooding risks along the major rivers that flow within the Bay Head of Bengal, such as the Brahmaputra or the Ganges Rivers, keeping in mind the lessons learned from managed realignment in UK (Pontee, 2015; Esteves, 2013; Esteves and Thomas, 2014).

6. Conclusion

This study presents a modeling-based comparison of conventional (raised dikes) against more innovative coastal defense schemes, relying on managed realignment of the dikes in order to mitigate marine flooding. Our numerical results suggest that the CDS implemented after Xynthia, which consists of raising the dikes, would not be sufficient to prevent from a similar event under a 2100 MSL. The managed realignment of the dikes and the implementation of large buffer zones would result in water level reductions locally exceeding 1.0 m and preventing from any flooding in areas at stake, such as urbanized areas. However, although potentially very promising, the implementation of such CDS would pose conflict of use with local farmers. A preliminary cost-benefit analysis revealed that the new CDS would cost significantly more than the conventional one, but would have other advantages more complicated to assess financially, such as the restoration of humid zones and the preservation of the seaview. These innovative CDS should be considered for other estuarine and deltaic environments prone to flooding around the world, such as in the Head Bay of Bengal or the Gulf of Mexico, remembering that ecological drawbacks could also arise.

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